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Spiral galaxy distance indicators based on near-infrared photometry[★]

Richard de Grijs^{1,2†} and Reynier F. Peletier^{3‡}

¹ *Astronomy Department, University of Virginia, PO Box 3818, Charlottesville, VA 22903-0818, USA*

² *Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, the Netherlands*

³ *Department of Physics, University of Durham, South Road, Durham DH1 3LE, United Kingdom*

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ABSTRACT

We compare two methods of distance determination to spiral galaxies using optical/near-infrared (NIR) observations, the $(I-K)$ versus M_K colour – absolute magnitude (CM) relation and the I and K -band Tully-Fisher relation (TFR).

Dust-free colours and NIR absolute magnitudes greatly enhance the usefulness of the NIR CM relation as a distance indicator for moderately to highly inclined *spiral* galaxies *in the field* (inclinations between $\sim 80^\circ$ and 90°); by avoiding contamination by dust the scatter in the CM relation is significantly reduced, compared to similar galaxy samples published previously. The CM relation can be used to determine distances to field spiral galaxies with $M_K > -25.5$, to at least $M_K \approx -20$.

Our results, supplemented with previously published observations for which we can – to some degree – control the effects of extinction, are consistent with a universal nature of the CM relation for field spiral galaxies.

High-resolution observations done with the *Hubble Space Telescope* can provide a powerful tool to calibrate the relation and extend the useful distance range by more than a factor of 2 compared to ground-based observations.

The intrinsic scatter in the NIR CM relation in the absolute K -band magnitudes is ~ 0.5 mag, yielding a lower limit to the accuracy of distance determinations on the order of 25%.

Although we find an unusually low scatter in the TFR (probably a statistical accident), a typical scatter in the TFR would yield distances to our sample galaxies with uncertainties of only $\sim 15\%$. However, one of the main advantages of the use of the NIR CM relation is that *we only need photometric data* to obtain distance estimates; use of the TFR requires additional kinematic data, although it can be used to significantly greater distances.

Key words: distance scale – galaxies: photometry – galaxies: spiral – galaxies: statistics – infrared: galaxies

1 PHOTOMETRIC DISTANCE INDICATORS

The study of highly-inclined disc-dominated galaxies offers the unique opportunity to avoid the confusing effects of interstellar extinction on the optical and near-infrared (NIR) appearance of their dominant (old) stellar disc population.

In this paper we use NIR absolute magnitudes and $I-K$ colours that were determined in those regions of our sta-

tistically complete sample of edge-on field galaxies that are least affected by extinction, to derive a “dust-free” colour – absolute magnitude (CM) relation. Dust-free colours and NIR absolute magnitudes greatly enhance the usefulness of the NIR CM relation as a distance indicator for moderately to highly inclined spiral galaxies in the field.

Alternatively, large galaxy surveys in the NIR facilitate the use of the NIR Tully-Fisher relation (TFR; Tully & Fisher 1977) as an accurate tool to obtain distances to spiral galaxies in clusters. In this paper we discuss the I and K -band TFRs derived from our sample galaxies and the accuracy with which they can be used to estimate distances to field spiral galaxies.

[★] Based on observations obtained at the European Southern Observatory, La Silla, Chile

[†] E-mail: grijs@virginia.edu

[‡] Present address: School of Physics and Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD

2 THE NIR COLOUR-MAGNITUDE RELATION

The tightness of the CM relation for *early-type* galaxies (as first established by Baum [1959] and de Vaucouleurs [1961]), makes it potentially useful as a distance indicator, as was first suggested by Sandage (1972). In this paper we investigate whether the NIR CM relation is also useful as a diagnostic tool to estimate distances to *spiral galaxies in the field*.

2.1 Elliptical versus spiral galaxies

Visvanathan & Griersmith (1977) extended the range of galaxy types from elliptical/S0 galaxies to early-type spirals (S0/a to Sab), and found (within the errors) exactly the same optical CM relation for the early-type Virgo cluster spirals as had been found for E/S0 galaxies, but with a larger excess *scatter* (see also Visvanathan & Sandage 1977; Griersmith 1980; Bower, Lucey & Ellis 1992b; Peletier & de Grijs 1998).

Despite the good agreement between the elliptical and spiral galaxy CM relations, later-type spiral galaxies occupy a different region in the CM diagram (e.g., Tully, Mould & Aaronson 1982; Mobasher, Ellis & Sharples 1986; Peletier & de Grijs 1998). Apart from this distinction between the loci of late-type spirals and E/S0's, Griersmith (1980) also noticed that differences in zero point of the CM relations seem to follow a systematic trend along the Hubble sequence: colours become systematically bluer for later Hubble types (see also Peletier & de Grijs 1998), although the slopes for the individual galaxy types are the same (within the errors) compared to each other and to E/S0 galaxies.

2.2 A universal CM relation?

Following the discovery of the CM effect for the early-type Virgo cluster members, many attempts have been made to unambiguously determine the universality of the relationship (e.g., Visvanathan & Sandage 1977; Visvanathan & Griersmith 1977; Griersmith 1980; Aaronson, Persson & Frogel 1981; Bower et al. 1992a,b). Provided that the CM relation is universally applicable it can be used as a distance indicator. In general, the UV-optical CM relation for *early-type galaxies* was found to be universal and independent of environment to a high degree (for a recent review see Ellis et al. 1997). However, the tests done to study the universality of the CM effect were challenged by a number of studies (e.g., Faber 1977; Burstein 1977; Larson, Tinsley & Caldwell 1980; Aaronson et al. 1981, and more recently Abraham et al. 1996 and van Dokkum et al. 1998), claiming that non-negligible environmental effects were playing a role in the observational evidence. To undertake an independent study of the universality of the CM relation, Bower et al. (1992a,b) obtained new observations of Virgo and Coma cluster galaxies. Their observations support the argument that a universal CM relation for cluster E/S0 galaxies, over the entire wavelength range, is likely, although the dispersion is expected to be considerable. Bower et al.'s (1992b) photometry allows the CM relation for early-type cluster galaxies to be used to estimate distances accurate to $\sim 20\%$ per galaxy.

In this paper we will use our own optical and NIR observations of edge-on spiral galaxies, supplemented with similar samples from the literature, to investigate the possible universality of the CM relation for *spiral galaxies in the field*.

2.3 Advantages of NIR observations

For the E/S0 galaxies in the Virgo cluster the change of colour with absolute magnitude is greatest in the ultraviolet, and decreases significantly towards redder wavelengths (Visvanathan & Sandage 1977, and references therein). However, the CM effect shows up again in the optical-NIR regime, in the sense that $V-K$ is bluer for intrinsically fainter galaxies (e.g., Aaronson et al. 1981, Tully et al. 1982). The usefulness of NIR observations of spiral galaxies in the field for measuring extragalactic distances depends on two main questions (e.g., Aaronson et al. 1981):

- (i) Do *spiral* galaxies in the field follow a universal CM relation in the NIR;
- (ii) If so, is the scatter sufficiently small for a useful application of the relation?

The main advantages of NIR observations compared to observations in the blue passbands are their relative insensitivity to contamination by the presence of young stellar populations and dust. The absorption corrections for dust in external galaxies, which are largest in the blue, are difficult and controversial; therefore, we were motivated to study the CM relation for our sample of edge-on spiral galaxies in the NIR, using $I-K$ colours and absolute K -band magnitudes.

In Peletier & de Grijs (1998) we find that the scatter in the NIR CM relation for (field) spiral galaxies can entirely be explained by observational uncertainties. Moreover, we show that the slope of the relation is steeper for spirals than for ellipticals. We can explain this if we assume that the CM relations for spiral and elliptical galaxies are intrinsically different, in the sense that the stars in spiral galaxies are younger than those in ellipticals and the fraction of young stars in a spiral galaxy (i.e., its “age”) is determined solely by the galaxy’s luminosity, and not by its environment. The CM relation formed by elliptical galaxies, on the other hand, is generally attributed to changes in metallicity (Peletier & de Grijs 1998, and references therein).

In Sect. 3 we discuss the nature of our observations and the corrections that have to be applied for an accurate study of the NIR CM relation. We supplement our data with recently published I and K -band data in Sect. 4. In Sect. 5 we discuss the implications of our results and look into the applicability of a tight NIR CM relation using *HST* observations. We discuss the accuracy of the NIR TFR in Sect. 6, and we give a summary of our results and conclusions in Sect. 7.

3 CONSTRUCTING THE CM RELATION

The observations of and the reduction techniques applied to our sample of highly-inclined spiral galaxies, as well as the resulting photometric accuracy, have been described in de Grijs (1997, 1998). Here, we summarize our selection criteria, applied to the galaxies in the Surface Photometry Cat-

alogue of the ESO-Uppsala Galaxies (ESO-IV; Lauberts & Valentijn 1989):

- Inclination selection: $i \geq 87^\circ$;
- Diameter selection: $D_{25}^B \geq 2.2$ (D_{25}^B : blue angular size at a surface brightness $\Sigma_B = 25$ mag arcsec $^{-2}$);
- Galaxy type selection: S0 – Sd, and
- Morphology selection: they should be non-interacting and undisturbed.

Although our NIR observations are relatively insensitive to disturbing dust effects (see, e.g., de Grijs, Peletier & van der Kruit 1997), we need to apply several corrections to the observed quantities before they can be used to study the CM relation.

3.1 Colour gradients and Galactic foreground extinction

Colour gradients in edge-on galaxies have not been studied extensively. In a few well-studied edge-on spiral galaxies, colour gradients parallel to the major axis were found to be negligible (e.g., Hamabe et al. 1980, Jensen & Thuan 1982, van der Kruit & Searle 1982), or show an increasingly blue disc population with increasing radius (e.g., Sasaki 1987, Aoki et al. 1991), although such gradients are generally small.

Vertical colour gradients in the discs of our sample edge-on galaxies are generally small or negligible (de Grijs et al. 1997, de Grijs & Peletier, in preparation); in fact, the vertical colour gradients are smaller than or of the same order as the observational errors for our I – K colour determinations. The only statistically significant vertical colour variation is the reddening due to dust in the galactic planes. As we showed in de Grijs & van der Kruit (1996) and de Grijs & Peletier (1997), the vertical scale height does not vary significantly as a function of wavelength, which indirectly shows the absence of any significant vertical colour gradient.

In de Grijs et al. (1997) we show that, once away from the dust lane, the vertical I – K colour profiles are generally (approximately) flat and featureless, indicating that the excess extinction in the I band (compared to that in the K band) is negligible at these heights above the galactic planes. The colours we use in this paper were determined from this (approximately) flat part of the vertical colour profile at the minor axis (at $1.5h_z \leq |z| \leq 3.5h_z$, where h_z is the exponential scale height), to avoid the reddening caused by the in-plane dust. Since young stellar populations are generally confined to regions close to the galactic planes, an additional advantage of determining colours away from the planes is that the contamination by emission from these young stellar populations is thus greatly reduced or negligible.

Peletier & Balcells (1997) showed, for their sample of 30 field spiral and lenticular galaxies, that the bulge colours on the minor axis and the inner disc colours taken in wedge apertures at 15° from the major axis at 2 K -band scale lengths are very similar. Therefore, the colour of an edge-on disc-dominated galaxy determined in a dust-free region at the minor axis can be considered as representative for the galaxy’s dominant (old) stellar population, under the assumption that vertical colour gradients in the old-disc population are smaller than the observational uncertainties.

To deal with Galactic reddening, we used the Galactic extinction values in the I and K' bands, $A_{G,I}$ and $A_{G,K'}$ given by Schlegel, Finkbeiner & Davis (1998), thereby assuming that the Galactic extinction can be approximated by a foreground dust screen. These full-sky dust maps are twice as accurate as the older reddening estimated by Burstein & Heiles (1978, 1984) in regions of low and moderate reddening and likely significantly more accurate in regions of high reddening (see also Hudson 1999). The Galactic extinction in the I and K' bandpasses was obtained assuming a standard $R_V = 3.1$ extinction law (Schlegel et al. 1998, their Appendix B).

3.2 Cosmological corrections and distance calibration

The corrections for the effects of redshift (K -corrections) are generally small in the NIR. For our sample galaxies the K -corrections for the I – K colours range from 0.00 – 0.04 mag (e.g., Schneider, Gunn & Hoessel 1983), depending on galaxy type (e.g., Coleman, Wu & Weedman 1980), see Table 1.

Heliocentric velocities for the majority of our sample galaxies were obtained by Mathewson, Ford & Buchhorn (1992) and Mathewson & Ford (1996), which provides us with a homogeneous data set to base our absolute magnitude calculations on. To obtain absolute magnitudes we applied the formula for the systemic velocities adjusted for the solar motion with respect to the centroid of the Local Group given by Richter, Tammann & Huchtmeier (1987, see also Schmidt & Boller 1992):

$$v_{LG} = v_\odot + \Delta v, \quad (1)$$

where

$$\begin{aligned} \Delta v = & -49.59 \cos \ell \cos b + 306.95 \sin \ell \cos b \\ & - 18.59 \sin b \end{aligned} \quad (2)$$

In Table 1 we give an overview of the observed and derived quantities used for the study of both the NIR CM and TF relations.

4 COMPARISON WITH LITERATURE SAMPLES

In Fig. 1a we have plotted the CM relation derived from our “dust-free” I – K colours (determined in the region $1.5h_z \leq |z| \leq 3.5h_z$) and the absolute K -band magnitudes, M_K^0 , both corrected for Galactic foreground extinction. To assess the importance of contamination by dust, in Fig. 1b we compare the NIR CM relation resulting from the use of integrated galaxy colours to that derived from the dust-free colours. It is clear that the importance of dust should not be underestimated: the integrated colours are systematically redder than the “dust-free” colours.

Careful examination of Fig. 1a reveals a rather peculiar distribution of the absolute K -band magnitudes of our sample galaxies, into two clumps and a single, bright galaxy. We believe that this is not due to any selection effects other than the availability of observing time with NIR arrays. The corresponding distribution of absolute I -band magnitudes,

Table 1. Basic properties of the sample galaxies

Columns: (1) Galaxy name (ESO-LV); (2) heliocentric velocity (Mathewson et al. 1992); (3) velocity correction for motion w.r.t. the centroid of the Local Group (Richter et al. 1987); (4)–(5) and (6)–(7) apparent I and K -band magnitudes and observational errors; (8) Galactic extinction in K' ; (9) $I-K$ colour excess (Schlegel et al. 1998); (10) and (11) $I-K$ color, corrected for Galactic foreground extinction, and observational error; (12) K -correction (interpolated from Schneider et al. 1980); (13) absolute K -band magnitude ($H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$), corrected for Galactic foreground extinction and the effects of redshift; (14) peculiar velocity with respect to the centroid of the Local Group (Mathewson et al. 1992).

Galaxy (ESO)	v_{\odot} (km/s)	Δv (km/s)	m_I^0 (4)	\pm (5)	m_K^0 (6)	\pm (7)	$A_{G,K'}$ (8)	$E(I-K)$ (mag) (9)	$(I-K)_0$ (10)	\pm (11)	$K\text{-corr.}$ (12)	M_K^0 (13)	$v_{\text{pec,LG}}$ (km/s) (14)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
026 -G 06	2748	-202.1	12.97	0.02	11.45	0.09	0.05	0.22	1.21	0.10	0.01	-20.38	49
141 -G 27	1922	-142.3	12.59	0.02	10.55	0.12	0.02	0.10	1.41	0.05	0.01	-20.26	150
142 -G 24	2119	-125.4	12.14	0.01	10.53	0.16	0.03	0.13	1.19	0.20	0.01	-21.01	-344
157 -G 18	1268	-206.9	12.26	0.02	9.78	0.17	0.01	0.03	1.33	0.10	0.00	-20.86	-304
201 -G 22	4014	-183.9	13.06	0.03	10.33	0.16	0.01	0.03	1.62	0.30	0.01	-22.90	-835
263 -G 15	2525	-310.5	10.82	0.01	9.02	0.15	0.07	0.30	1.69	0.10	0.01	-22.70	–
286 -G 18	9162	-34.9	12.12	0.01	10.42	0.11	0.02	0.06	1.71	0.07	0.03	-24.44	-554
311 -G 12	1128	-279.7	9.29	0.01	7.21	0.07	0.14	0.61	1.55	0.05	0.00	-22.44	–
315 -G 20	4843	-300.3	12.19	0.01	9.11	0.19	0.08	0.35	1.40	0.07	0.02	-24.18	–
340 -G 09	2546	-20.1	13.51	0.07	11.32	0.16	0.02	0.09	1.20	0.15	0.01	-20.62	-58
358 -G 29	1776	-119.1	10.34	0.01	8.25	0.09	0.01	0.02	1.43	0.05	0.01	-22.85	–
383 -G 05	3637	-240.1	11.83	0.02	8.93	0.22	0.02	0.09	1.61	0.03	0.01	-23.73	–
416 -G 25	4998	-71.6	12.46	0.03	10.34	0.18	0.01	0.05	1.56	0.08	0.02	-23.45	-1118
435 -G 14	2697	-285.9	12.38	0.05	10.09	0.10	0.03	0.15	1.65	0.12	0.01	-22.76	-1522
435 -G 25	2470	-288.3	10.89	0.03	8.39	0.11	0.03	0.13	1.79	0.10	0.01	-23.49	-262
437 -G 62	2850	-289.8	10.57	0.01	8.31	0.19	0.03	0.12	1.71	0.20	0.01	-23.73	–
446 -G 18	4843	-204.9	12.59	0.02	10.15	0.10	0.02	0.10	1.71	0.25	0.02	-23.33	-660
446 -G 44	2793	-204.2	12.37	0.04	10.20	0.12	0.03	0.11	1.58	0.05	0.01	-22.35	-847
460 -G 31	5759	25.3	12.07	0.02	9.94	0.15	0.08	0.33	1.82	0.15	0.02	-23.70	216
487 -G 02	1755	-153.8	11.38	0.01	8.83	0.12	0.01	0.04	1.57	0.05	0.01	-22.77	-656
509 -G 19	10727	-218.9	12.20	0.01	9.55	0.13	0.03	0.09	2.02	0.08	0.04	-25.56	–
564 -G 27	2178	-259.4	12.12	0.09	9.66	0.11	0.06	0.24	1.66	0.10	0.01	-22.65	-1166

which were obtained for about twice as many of our sample galaxies, does not show any significant subclumping, although the two brightest galaxies are ~ 1 mag brighter than the third brightest galaxy observed as part of our project.

In Fig. 2 we compare our results with those of other galaxy samples published recently. Only very few samples with high-quality K -band observations have been published to date:

- (a) The sample of Bershadsky et al. (1994) and Bershadsky (1995) consists of 171 field galaxies of all types, selected from three high Galactic latitude fields (where the Galactic extinction is low), of which a subset of 143 is statistically representative in its sampling of the apparent colour distribution of galaxies. The median redshift of the sample galaxies is $z = 0.14$. Absolute magnitudes were determined using luminosity distances, corrected for cosmological effects.
- (b) De Jong's (1996b) sample is a diameter-limited sample of 86 (nearly) face-on spiral galaxies. His absolute magnitude calculations are based on heliocentric velocities, corrected for Virgocentric infall using the model of Kraan-Korteweg (1986; de Jong, priv. comm.), and taking into account the Galactic foreground extinction estimates of Burstein & Heiles (1978, 1984).

- (c) The data presented by Andredakis, Peletier & Balcells (1995) and Peletier & Balcells (1997) consists of 37 field disc galaxies of types S0 to Sbc, uniform in orientation on the sky, for 30 of which NIR observations are available. To obtain absolute magnitudes, they used the Galactic standard-of-rest corrections given by de Vaucouleurs et al. (1991). Corrections for foreground extinction were only applied to their I -band observations, since the K -band corrections were smaller than their observational errors.
- (d) Tully et al.'s (1996) sample was taken from the Ursa Major cluster; they present I and K' -band observations of a magnitude-limited sample of 70 disc-dominated galaxies.

After scaling these and our observations to the same cosmology (using $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$), we find that the most significant deviations from our CM relation are exhibited by samples (a) (Bershadsky et al. 1994, Bershadsky 1995), and (d) (Tully et al. 1996).

In either of these samples the reddening due to dust is unknown. Bershadsky et al. (1994) and Bershadsky (1995) corrected their integrated I and K -band colours neither for Galactic nor for internal extinction in their sample galaxies. Any comparison between our dust-free and their integrated colours will therefore show an additional discrepancy due to extinction effects. Moreover, their redshift distribution is

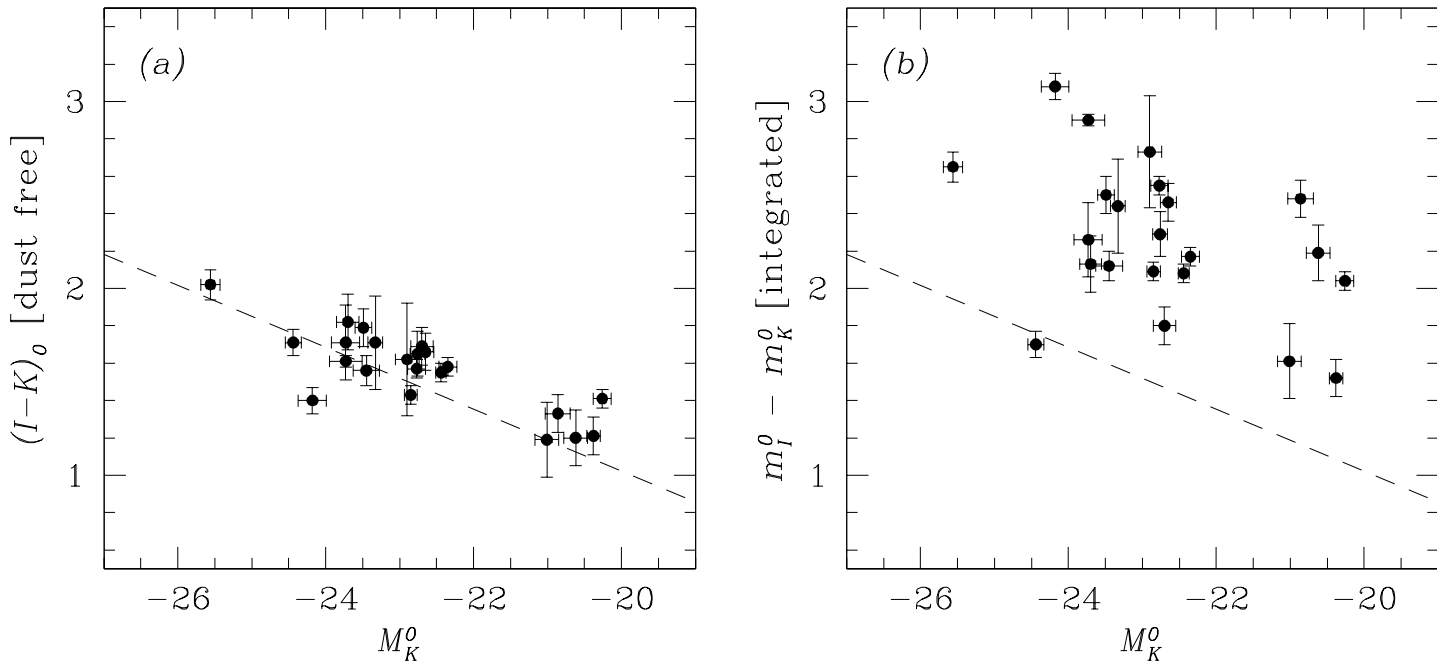


Figure 1. (a) Correlation between absolute K -band magnitude, M_K^0 , and dust-free $I-K$ colours. The best-fitting NIR CM relation is indicated by the dashed line, for which the parameters are given in Table 2; (b) Corresponding CM relation derived from the integrated galaxy colours. Almost all data points are located redwards from the best-fitting CM relation shown in Fig. 1a, due to internal interstellar extinction. All observational quantities have been corrected for Galactic foreground extinction.

different from those of the other samples, so that we also have to take into account possible evolutionary effects when comparing these relations.

Tully et al. (1996) corrected their photometry for both Galactic foreground and internal extinction, using Tully & Fouqué’s (1985) inclination corrections. Although this method is to first order useful for low and intermediate inclinations, there are severe problems for highly-inclined galaxies. Moreover, for the analysis of a combined sample of spiral galaxies, extinction effects should be treated uniformly. In addition, Tully et al.’s (1996) sample was drawn from a cluster population, whereas the other samples consist (mainly) of field galaxies. Until it has been established unambiguously that environmental effects do not play a role in the determination of the CM relation for spiral galaxies, we cannot use a mixture of field and cluster galaxy samples to base our conclusions on. Therefore, we will consider field galaxy samples only in our analysis of the NIR CM relation in this paper.

Sample (b) (de Jong 1996b) consists of disc-dominated (nearly) face-on galaxies. The face-on orientation ensures that the effects of internal extinction on the integrated $I-K$ colours are small (but not necessarily negligible), as opposed to more inclined galaxies, since less light is obscured by the dust lane, because the light dominating these colours is emitted by the old-disc stellar population located in front of the dust component (which is concentrated in the galactic plane region). De Jong (1996a) argues that the colours and colour gradients observed in his sample of face-on galaxies

are determined by intrinsic physical processes in the discs rather than by extinction effects. However, it is likely that the larger scatter in his CM relation compared to ours is at least partly due to extinction effects affecting his integrated colours (which are likely greater for these colours than for our “dust-free” colours, due to line-of-sight integration effects), in addition to the effects of colour gradients across his face-on discs, which vary as a function of galaxy type.

Finally, sample (c) (Andredakis et al. 1995, Peletier & Balcells 1997) consists of early-type disc galaxies (S0–Sbc), of which they studied the disc and bulge components separately. From the orientation of the individual galaxies they obtained dust-free colours on the non-obscured side of the galactic planes. In addition, Peletier & Balcells (1997) assessed the importance of internal extinction by studying the change in the position of the galactic centres as a function of wavelength. Such a shift occurs when a dust lane in front of the true centre obscures more light on one side of the centre than on the other, causing the observed centre to shift as a function of optical depth, or passband. Their centre shift is in general within the typical errors, which provides additional support to the assumption that extinction does not play a major role in their colour determinations.

In Table 2 we compare the parameters of the NIR CM relation derived from our sample of 22 edge-on disc galaxies with both the CM parameters derived from the comparison samples in Fig. 2, and those obtained from supplementing our data with samples (b) and (c), the “composite” CM

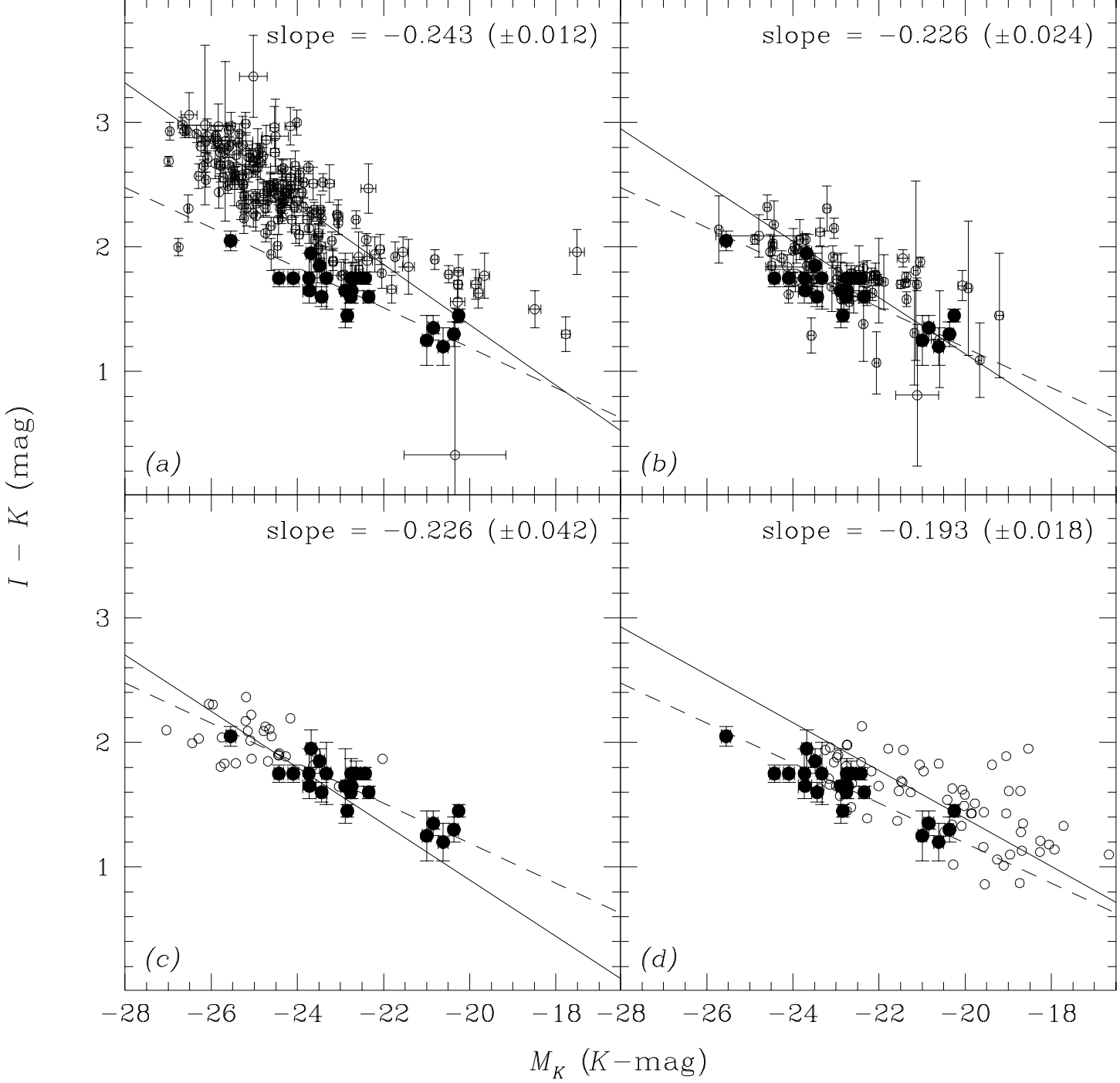


Figure 2. Comparison of our M_K vs. $(I-K)$ CM relation with previously published data. The filled circles show our sample galaxies; the open circles represent previously published data. The best-fitting NIR CM relations for the literature samples are indicated by the solid lines; for comparison, the dashed lines represent the mean CM relation derived from the data presented in this paper. (a) Bershadsky et al. (1994), Bershadsky (1995); (b) de Jong (1996b); (c) Andreidakis et al. (1995), Peletier & Balcells (1997); (d) Tully et al. (1996).

Table 2. Comparison of the NIR CM parameters:

$$(I - K) = aM_K + b$$

Columns: (1) Sample; (2) and (3) CM slope, a , and its error; (4) and (5) Intercept, b , and its error; (6) Scatter in the CM relation.

Sample (1)	a (2)	\pm (3)	b (4)	\pm (5)	σ (mag) (6)
(a) Bershadsky	-0.243	0.013	-3.48	0.30	0.256
(b) de Jong	-0.226	0.024	-3.38	0.55	0.222
(c) Peletier	-0.226	0.042	-3.63	1.04	0.173
(d) Tully (<i>all</i>)	-0.193	0.018	-2.46	0.37	0.242
(d) Tully ($T \geq 4$)	-0.199	0.025	-2.67	0.51	0.256
our	-0.156	0.021	-1.99	0.48	0.133
without brightest	-0.157	0.024	-1.99	0.55	0.137
composite	-0.189	0.013	-2.59	0.31	0.205

relation, for which we are fairly confident that extinction effects are small.

One might wonder to what extent the slope and zero point of our CM relation are determined by the brightest, outlying galaxy. We redetermined these parameters for our sample, excluding this brightest member, and found essentially identical results (see Table 2, for the sample “without brightest”). This was of course to be expected, in view of the good agreement between our data on the one hand, and the similar samples used to construct the composite CM relation on the other.

The dashed line in Fig. 3 shows the composite NIR CM relation. The best-fitting CM relation derived from our data alone is shown by the dotted line. The close agreement between both CM relations supports our assumption that we can indeed compare our observations to samples (b) and (c). In fact, the good agreement between our sample and samples (b) and (c) leads us to note that *the NIR CM relation for the old-disc population of spiral galaxies in the field appears to be universal* (see Peletier & de Grijs 1998).

In Table 2 we also give the standard deviations of the observed data points with respect to the best-fitting linear CM relation, which are indicative of the scatter in these CM relations. The best-fitting relations were determined by means of a bivariate minimization algorithm. It is immediately clear that the scatter in the CM relation determined from our dust-free data points is of order 40% smaller than for both samples (b) and (c).

Only if we can put firm constraints on the scatter in the CM relation for field spiral galaxies, it may be useful as a distance indicator. Therefore, we compared the scatter in the CM relation that we obtained from our dust-free disc colours to that from previous studies.

From a detailed photometric study of Virgo and Coma cluster members, Bower et al. (1992b) found that for elliptical galaxies the scatter in the CM relation is dominated by the observational errors. The inclusion of S0 and early-type spiral galaxies into their sample increases the observed scatter in the optical-NIR ($V-K$) CM relation. To be able to compare our results to those of Bower et al. (1992b), we applied the least-squares fitting technique we used to their data, and found close matches between our and their values

for the r.m.s. scatter. Therefore, we can directly compare the scatter estimates obtained from the samples listed in Table 2 to Bower et al.’s (1992b) results.

Although it is obvious that the scatter in samples containing spiral galaxies is significantly larger than in samples containing only E/S0 galaxies (see also Visvanathan & Sandage 1977, Peletier & de Grijs 1998), we have shown that by avoiding the disturbing effects of the in-plane dust lane the scatter in the spiral galaxy NIR CM relation can be reduced significantly (e.g., Fig. 1).

Therefore, *a NIR CM relation for spiral galaxies based on dust-free colours may in principle be useful as a diagnostic to estimate distances*. It provides independent distance estimates based on observational parameters.

5 IMPLICATIONS

5.1 The shape of the CM relation

Lasker (1970) was the first to notice that the CM relation seems to flatten towards the brighter galaxies in his sample, although in Fig. 14 of de Vaucouleurs (1961) one can already see this effect. Frogel et al. (1978) and Tully et al. (1982) also note that the $V-K$ colour of their brightest sample galaxies is relatively independent of luminosity compared to the fainter groups.

With this relative flattening in mind, a linear fit to the CM relation may not be the best representation of the correlation. However, flattening effects are second-order effects; to first order linear fits should be sufficient for the determination of distance moduli.

To investigate a possible flattening trend in our data we computed the mean $I-K$ colours in absolute magnitude bins of 0.5 mag, of which the result is shown as the solid line in Fig. 3; the error bars indicate the dispersion in the data points in each bin. Although we are dealing with relatively few data points, a flattening is indeed appreciated at the bright end of the relation. This means that the old stellar populations in the brightest – or largest – disc galaxies have a roughly constant intrinsic $I-K$ colour. Thus, for spiral galaxies with $M_K < -25.5$ the CM relation cannot be used as a diagnostic tool for distance determinations. At the faint end too few data points are available to draw firm conclusions about the shape of the CM relation, but it seems likely that the correlation is maintained down to (field) spiral galaxies as faint as $M_K \approx -20$.

5.2 Applications of a tight CM relation

As we argued in Sect. 4, a NIR CM relation for spiral galaxies based on dust-free colours may in principle be useful as a diagnostic to estimate distances: it provides independent distance estimates based on observational parameters.

For distance determinations to individual spiral galaxies, we have to take into account the scatter in and the shallow slope of the CM relation, as well as the observational errors, which will result in relative distances accurate to $\sim 35\%$ for the observations presented in this paper. This accuracy estimate is based on the observed dispersion (i.e., the combination of observational and intrinsic scatter) in the NIR CM relation *in the absolute K -band magnitudes* (~ 0.7

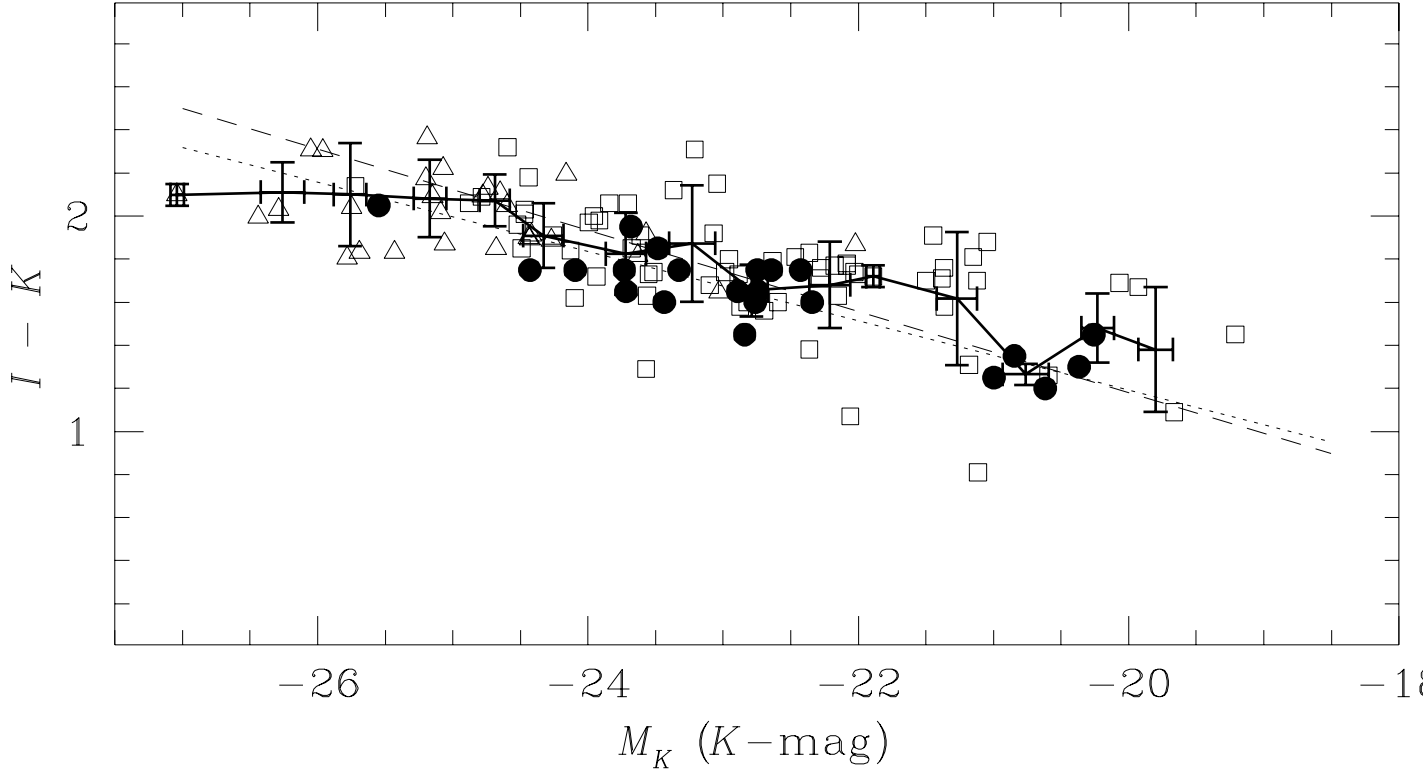


Figure 3. Composite CM relation, derived from samples (b) and (c) and supplemented with the observations presented in this paper. Our observations are shown as filled circles; the open squares correspond to sample (b), the open triangles to sample (c). The best-fitting composite CM relation is indicated by the dashed line; its parameters are listed in Table 2. The NIR CM relation derived from the observations presented in this paper is indicated by the dotted line. The solid line was obtained by binning the data points in M_K bins of 0.5 mag; the error bars indicate the dispersion in the data points in each bin.

mag; i.e. the dispersion along the horizontal axis in Fig. 1a). For a “typical” sample galaxy, the observational dispersion in the absolute magnitude determinations (taking into account the uncertainties in the apparent magnitude and the correction for the motion with respect to the Local Group) is ~ 0.45 mag, which means that the intrinsic scatter in the NIR CM relation among galaxies is ~ 0.5 mag for the absolute K -band magnitude determinations. Although it is likely that part of this intrinsic scatter is caused by the peculiar velocities of our sample galaxies with respect to the Hubble-flow movement of the centroid of the Local Group, small-number statistics prevent us from reaching conclusive evidence for this: peculiar motions are available for only 15 of our 22 sample galaxies (Table 1; Mathewson et al. 1992). For instance, correcting the absolute magnitudes for the effects of the peculiar velocities results in a dispersion in M_K of 0.994 mag, compared to 0.640 mag before correction of these 15 sample galaxies. The dispersion in $(I-K)$ increases from 0.102 to 0.161 mag, based on bivariate fits.

The observational uncertainties in the apparent K -band magnitudes discussed in this paper are largely due to the relatively shallow (“snap-shot”) nature of the observations, as well as to the rapidly varying sky background in the K band (see de Grijs [1997], and de Grijs et al. [1997] for a discussion of the relevant photometric accuracy achieved in this project). This rapid variability requires that short (< 60 s) object and sky observations, of equal integration

times, are taken alternately, in order to correct for these background variability effects. Obviously, a greater number of such observations will smooth out any remaining effects due to the varying background on the one hand, and increase the signal-to-noise (S/N) ratio in the galactic outskirts on the other, thereby improving the photometric accuracy of the integrated K -band magnitudes significantly. In addition, to unambiguously establish a uniform spiral galaxy CM relation, the distances to the sample galaxies need to be known to high accuracy. For our present sample, uncertainties in the absolute K -band magnitudes can be reduced by the determination of distances that are more accurate than those used in this paper, which are based on recessional velocities.

Therefore, by obtaining high-quality observations of and improved distances to moderately or highly inclined galaxies, the accuracy of this method can be enhanced by reducing the observational scatter in the apparent K -band magnitudes to a lower limit of ~ 0.02 mag. The accuracy will thus be limited by the intrinsic dispersion in the NIR CM relation in the absolute K -band magnitudes (~ 0.5 mag). Because of this intrinsic scatter, the maximum accuracy of distance determinations to spiral galaxies that can be reached using this relation will therefore be $\sim 25\%$. Note that this accuracy approaches the 20% accuracy of Bower et al. (1992b) for early-type galaxies, for which the intrinsic scatter in the CM relation is significantly smaller.

The intrinsic dispersion in absolute K -band magnitudes

in the CM relation for field spiral galaxies is most likely caused by the non-negligible effects of different degrees of active star formation, star formation histories, ages, metallicities, and extinction, even at the z heights at which we determined our “dust-free” colours, and perhaps non-negligible vertical colour gradients in the discs of our sample galaxies (Peletier & de Grijs 1998; de Grijs & Peletier, in preparation). In view of the expected variation of all these parameters, it is even more surprising to find a very tightly constrained NIR CM relation for field spiral galaxies.

5.2.1 How Hubble Space Telescope observations can contribute to the calibration

Since the galaxies need to be spatially resolved, high-resolution observations done with the *Hubble Space Telescope* (*HST*) can provide a powerful tool to minimize the observational scatter and extend the useful distance range. Such observations may therefore provide the means to calibrate the relation. We will demonstrate this in the following exercise:

- *Model galaxy.* We assume that the intrinsic major-to-minor axis diameter of a “typical” spiral galaxy disc is 9 : 1 (e.g., Guthrie 1992), and the scale height ratio of the dust to the stellar disc is 1 : 2 (following the standard models in Huizinga 1994; see also Xilouris et al. [1999] for case studies), whereas the dust disc is embedded in the stellar disc according to the so-called “triplex model” (e.g., Disney, Davies & Philipps 1989). Furthermore, either disc is assumed to be of exponential form, both radially and vertically.
- *Inclination restrictions.* The requirement that we need to be able to control – to some extent – the effects of extinction restricts the useful inclination range to inclinations between $\sim 80^\circ$ and 90° . The lower inclination limit is set by the fact that at $i \simeq 80^\circ$ the dust lane will be observed at the outer rim of the projected galactic disc nearest to the observer. This implies that, from this inclination upwards, the upper stellar layer at the far edge of the disc will not significantly be affected by the effects of extinction. For higher inclinations, an increasingly large dust-free area will be available for colour measurements, divided in two parts by the high-extinction in-plane dust lane.
- *Size restrictions.* For an unambiguous determination of these dust-free colours, one will ideally need a dust-free area of at least three resolution elements containing galactic emission brighter than the limiting magnitude or S/N ratio. With the superb angular resolution of the *HST*, we will be able to reduce the minimum projected sizes of the useful candidate galaxies considerably. In the NIR, the most suitable *HST* instrument is the *Near-Infrared Camera and Multi-Object Spectrometer* (*NICMOS*), which has a pixel size of $0.''075$ (camera 2) and a FWHM for point sources of ~ 1.3 pixels ($0.''10$) at $1.1\mu\text{m}$ to 2.5 pixels ($0.''19$) at $2.2\mu\text{m}$ (Krist & Hook 1997). The inclusion of a red optical passband (e.g., I) requires additional imaging with the *Wide Field Planetary Camera 2* (*WFPC2*); the pixel scale of the *Planetary Camera* is $0.''0455$, with a point source FWHM of about 2.5 pixels ($\sim 0.''11$, depending

on wavelength). Since the *WFPC2* characteristics fall inside the parameter range for *NICMOS* camera 2, we will restrict ourselves to the possibilities provided by the use of *HST NICMOS* observations in the remainder of this exercise.

Along the galaxies’ minor axes, the useful area for colour determinations is, for all inclinations ($80^\circ \leq i \leq 90^\circ$) and assuming a minimum dust-free extent of 3 resolution elements on the side nearest to the observer, $\sim 0.''29$ and $\sim 0.''56$ for the J and K bands, respectively. Under the additional assumptions outlined at the beginning of this paragraph, and by using Hubble’s (1926) relation between a galaxy’s inclination and its axis ratio, the minimum projected size of a candidate galaxy in the J band is $1.''6 \times 8.''5$ to $1.''2 \times 10.''5$ for inclinations of 80° to 90° ; in the K band the different FWHM converts to projected sizes of $3.''0 \times 16.''4$ to $2.''3 \times 20.''2$ for the same inclination range. We are thus limited by the sizes required by the K -band imaging.

Because of the high resolution of the *HST* one will be able to resolve a galaxy of a given size (determined by the limiting magnitude or S/N ratio of the observations) out to larger distances than when observed with (seeing-limited) ground-based telescopes. To get an indication of the usefulness of the NIR CM relation as a function of distance we obtained *HST* archive observations of NGC 891. This edge-on Sbc galaxy is comparable in size and appearance to the Galaxy. We used observations in the optical F606W passband (160s) and the NIR F160W filter (192s).

In the (wide) V -band observations, the maximum useful dust-free region on the minor axis, where the galactic V -band surface brightness $\Sigma_V \leq 25 \text{ mag arcsec}^{-2}$, is $(33.''0 \pm 0.''5)$, which corresponds to $(1.50 \pm 0.02) \text{ kpc}$ at its distance of 9.5 Mpc (van der Kruit & Searle 1981, see also Keppel et al. 1991). The minimum dust-free region on a galaxy’s minor axis containing three independent resolution elements is $0.''56$, which is required by the need for *NICMOS* K -band imaging, as explained above.

From this argument it follows immediately that we can use galaxies of similar size as NGC 891 for the construction of a NIR CM relation up to distances of $(560 \pm 5) \text{ Mpc}$. For comparison, ground-based observations can be used for similar galaxies out to distances of only $\sim 210 \text{ Mpc}$, under optimal seeing conditions (FWHM $\sim 0.''5$). In Fig. 4 we show the difference between the results obtained using *HST* observations and ground-based observations taken under such optimal seeing conditions for edge-on galaxies like those presented in this paper. To construct this figure, we have adopted the assumptions about the galactic structure outlined above, and a major axis diameter of $D_{25}^B = 13.''5$ for NGC 891 (RC3), corresponding to a linear size of 37.3 kpc .

From a comparison between the optical and the NIR *HST* observations of NGC 891, with integration times of the same order, it is clear that the NIR observations do not reach the galactic outskirts at similar S/N ratios as in the optical. Therefore, if we base our conclusions on this particular case, the successful use of the NIR CM relation for distance estimates depends on the faintest surface brightness levels that can be achieved in the NIR. However, this does not need to be the case for all galaxies, as it depends on parameters, such as intrinsic colours, sky background (which is

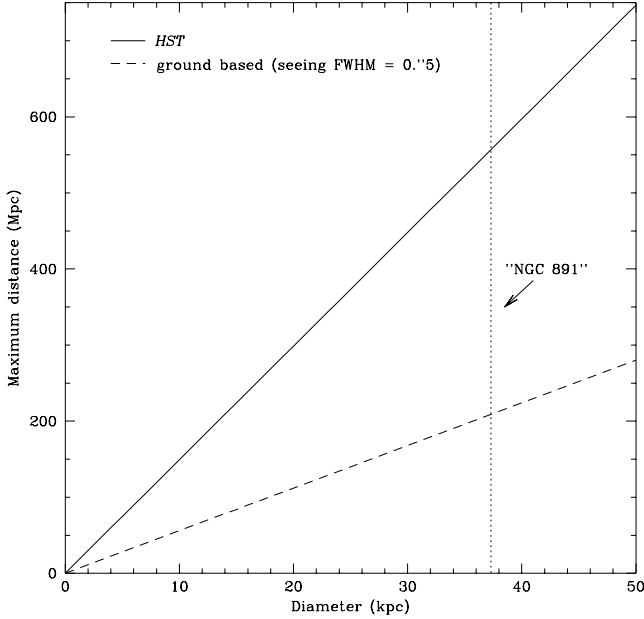


Figure 4. Comparison between the maximum distances out to which the NIR CM relation can be used successfully to obtain distance estimates for *HST* and ground-based observations under optimal seeing conditions. The power of space-based observations for distance determinations using this relation is clear.

supposed to be very low for space-based NIR observations), etc.

In summary, high-resolution observations done with the *HST* can significantly increase the number of useful galaxies and hence provide a powerful tool to calibrate the CM relation for spiral galaxies, reduce the observational scatter, and extend the useful distance range by more than a factor of 2 compared to ground-based observations. The useful projected galaxy sizes are limited by the *K*-band resolution, which translates to minimum sizes from $3.''0 \times 16.''4$ to $2.''3 \times 20.''2$ for inclinations of 80° to 90° . Obviously, *I* (or *J*) and *K*-band observations of galaxy fields from the *HST* data archive (e.g., the *Hubble Deep Fields*, among others) would be well suited to undertake such a programme.

6 THE NIR TULLY-FISHER RELATION

For the majority of our sample galaxies a homogeneous data set containing both the maximum (optical) rotational velocities and total (apparent) *I*-band magnitudes was provided by Mathewson et al. (1992) and Mathewson & Ford (1996). In de Grijs (1997, 1998), we compared our *I*-band photometry to that of Mathewson et al. (1992) and Mathewson & Ford (1996). From the detailed comparison of our photometry to theirs it was shown that we can accurately reproduce their results ($\langle m_{I,\text{our}} - m_{I,\text{Mathewson}} \rangle = -0.07 \pm 0.13$; de Grijs 1997, 1998).

The *I* and *K*-band TFRs derived from our absolute magnitudes, and supplemented with Mathewson's rotational velocity data, are shown in Fig. 5. We did not correct our

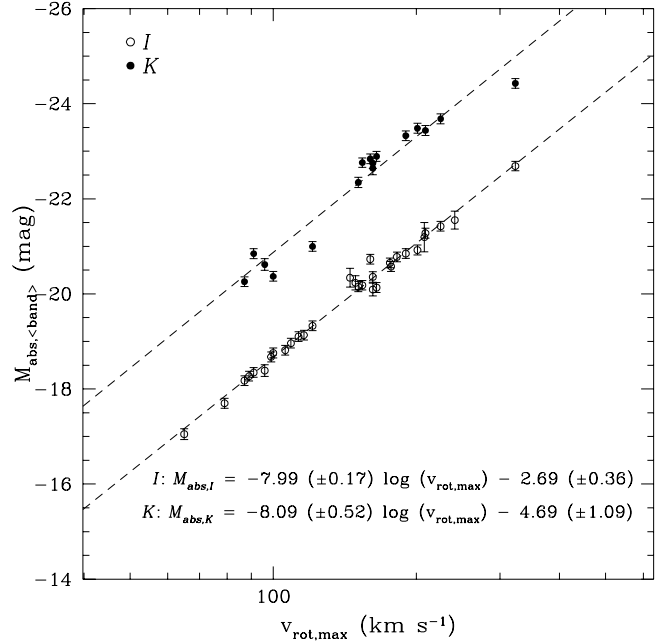


Figure 5. *I* and *K*-band TFRs derived from our observations (no internal extinction correction was applied).

integrated magnitudes for the effects of internal interstellar extinction; inclination corrections that aim to correct internal extinction are generally not applicable to highly inclined galaxies. Moreover, the amount of extinction in a galaxy varies as a function of galaxy type, as well as among galaxies of the same type (see, e.g., de Grijs et al. 1997, 1998, and references therein). It is therefore likely that the scatter in the *I* and *K*-band TFRs derived from our observations is at least partly caused by internal extinction. However, note that errors in the TF distances are generally dominated by uncertainties in the inclinations of the sample galaxies.

6.1 The scatter in the Tully-Fisher relation

A good measure of the accuracy of the TFR can be obtained by assessing the scatter in the relation. In the *I* and *K* bands, the TFR r.m.s. scatter is 0.145 and 0.296 mag, respectively, based on bivariate fits (e.g., Giovanelli et al. 1997, Verheijen 1998). The scatter in the *K*-band TFR is significantly larger than that in the *I* band. This is probably caused by the fact that both the S/N ratio in our *K'*-band images is significantly smaller and the effects of the varying sky background are much greater in *K'* than in the *I*-band observations, causing the larger uncertainties, and thus observational scatter, in the *K*-band magnitudes. We are confident that the scatter in the *K* band TFR due to internal extinction is very small in comparison, since the *K*-band vertical surface brightness profiles exhibit hardly any signatures of either a regular dust lane or a patchy dust distribution, even in those galaxies showing pronounced dust lanes in the optical passbands (de Grijs et al. 1997).

The r.m.s. scatter in our *I*-band TFR is small compared to that found in previous studies (for a discussion see Bern-

stein et al. 1994, Giovanelli et al. 1997): only Bernstein et al. (1994) reported a significantly smaller scatter, of $\sigma = 0.10$ mag, based on a sample of 22 galaxies. Giovanelli et al. (1997) argue that TF fits with scatter smaller than 0.25 mag are likely to be statistical accidents, which can occur when galaxy samples are small. They base this argument on the detailed study of the TFR for a large number of galaxies in 24 clusters. Giovanelli et al. (1997) determined the scatter in the I -band TFR for the individual clusters; their observational scatter varies between 0.12 and 0.36 mag (based on bivariate fitting routines). With this statistically significant result in mind, we believe that the low scatter found in this paper is indeed a statistical accident. Additional support for this assumption is lent by the fact that the scatter in the CM relation increases (in either of the quantities) if we correct for the effects of peculiar motions, as shown in Sect. 5.2.

To our knowledge, studies of the TFR in the NIR K (or K') band are scarcely available to date. From Fig. 10 of Tully & Verheijen (1997), we derive a scatter of 0.531 mag in the K' -band TFR of Ursa Major cluster galaxies, based on a bivariate fit; for the low and high surface brightness galaxies in this figure, we derive a scatter of 0.654 and 0.363 mag, respectively. In addition, in a detailed study of a volume-limited complete sample of ~ 40 Ursa Major cluster galaxies Verheijen (1997) finds that the smallest observed TFR scatter in his galaxy sample is 0.29 mag in K' , consistent with no intrinsic scatter.

Giovanelli et al. (1997) applied a type-dependent correction for internal extinction to their observations, which varies between 0.50 and 1.00 mag in the I band, corresponding to 0.12 – 0.23 mag in the K band (assuming an $R_V = 3.1$ extinction law, e.g., Schlegel et al. 1998). If we apply a similar extinction correction to our data, we find a scatter in the I -band TFR of 0.225 mag (as opposed to 0.145 mag for the uncorrected measurements), and a scatter of 0.316 mag in the K -band TFR (compared to 0.296 mag before extinction correction), which is entirely consistent with Giovanelli et al.’s (1997) results.

From their detailed analysis of the scatter in the TFR, Giovanelli et al. (1997) concluded that the average total scatter in their measurements of a statistically significant number of galaxies in 24 clusters is ~ 0.35 mag. If we assume that this is a typical value for the scatter in any well-sampled TFR, the accuracy of the TF distance to a “typical” galaxy in our sample would amount to $\sim 15\%$.

When comparing our TF results with the accuracy of distance determinations using the NIR CM relation, we note that, due to the shallower slope of the CM relation, the effects of uncertainties in the distance estimates are relatively more important for the calibration of the spiral galaxy CM relation than for the TFR. On the other hand, one of the main advantages of the use of the NIR CM relation is that *we only need photometric data* to obtain distance estimates, whereas use of the TFR requires additional kinematic data.

6.2 Distance estimates: Tully-Fisher vs. Colour-Magnitude

In Sect. 5.2.1 we estimated that the NIR CM relation can be used to obtain distances to galaxies similar to the Galaxy or NGC 891 up to (560 ± 5) Mpc, if *HST*-based photometry

and resolution can be obtained. Following similar lines of argument, in this section we will estimate the corresponding maximum TF distance to a Galaxy-type system that can still be determined unambiguously. To do so, we will restrict ourselves to ground-based rotation curve measurements, since they are most readily available in the literature, and most easily obtained.

Based on a statistical analysis of a spiral galaxy sample designed for TF applications, Courteau (1997) has shown that the best measure of TF velocity is given at the location of peak rotational velocity of a pure exponential disc. Alternatively, one can use the 20% width of the H I velocity profile. Although this latter method does not make any *a priori* assumptions about the luminosity profile or shape of the rotation curve, its accuracy is not optimal (Courteau 1997).

If we restrict ourselves to optical observations, one needs at least 5 resolution elements with reliable S/N ratios to obtain an accurate measure of the rotation curve. Under optimum seeing conditions (FWHM $\sim 0.''5$), this corresponds to a minimum angular diameter of a galactic disc of $\sim 2.''5$. A Galaxy-type system like NGC 891, with a linear diameter of 37.3 kpc (Sect. 5.2.1), would therefore be useful for distance estimates up to ~ 3.1 Gpc (~ 5.5 times as far as the maximum CM distances). Obviously, the use of H I observations will increase this distance estimate significantly.

The main disadvantage of the use of the TFR versus the CM relation for distance estimates to relatively nearby, *highly inclined* galaxies is that the conversion of apparent to face-on corrected magnitudes is controversial and model dependent.

7 SUMMARY AND CONCLUSIONS

In this paper we have looked at two methods of distance determination to spiral galaxies in the field using optical/NIR observations, the $(I-K)$ vs. M_K colour – absolute magnitude relation and the I and K -band Tully-Fisher relation. We have used “dust-free” colours to achieve greater accuracy for distance determinations using the CM relation compared to the integrated galaxy colours that are generally used for this exercise. Our main conclusions are the following:

- Our data, supplemented with observations taken from the literature form a well-constrained composite spiral galaxy CM relation; it appears that the NIR CM relation for the old-disc population of spiral galaxies in the field is universal.
- By avoiding the disturbing effects of the in-plane dust lane the observational scatter in the CM relation can be reduced significantly. Therefore, the NIR CM relation for field spiral galaxies, based on dust-free colours, may in principle be useful as a diagnostic tool to estimate distances with an accuracy of $\sim 25\%$. This accuracy is limited by the intrinsic dispersion of the NIR CM relation in the K -band absolute magnitudes (~ 0.5 mag).
- High-resolution observations done with the *Hubble Space Telescope* can provide a powerful tool to reduce the observational scatter, calibrate the relation, and extend the useful distance range (by more than a factor of 2 compared to ground-based observations). The use-

ful projected galaxy sizes are limited by the *NICMOS* *K*-band resolution, which translates to minimum sizes from $3.''0 \times 16.''4$ to $2.''3 \times 20.''2$ (at the limiting magnitude or S/N ratio) for inclinations $80^\circ \leq i \leq 90^\circ$.

- We found a scatter in the *I* and *K*-band TFRs of 0.145 and 0.296 mag, respectively. Although, to date, these values are among the lowest found in these passbands, they are likely statistical accidents, caused by our relatively small sample size (see Giovanelli et al. 1997).
- Due to the shallower slope of the CM relation, the scatter is relatively more important for the determination of distances via this method than for distance determinations using the TFR: typically, TF distances can be determined with an accuracy of $\sim 15\%$ (and to significantly greater distances), as opposed to the $\sim 25\%$ accuracy achieved using the NIR CM relation. However, one of the main advantages of the use of the NIR CM relation is that *we only need photometric data* to obtain distance estimates, whereas use of the TFR requires additional kinematic data.
- Although a linear fit is a good first-order approximation to the composite NIR CM relation, the old-disc populations of the brightest disc galaxies ($M_K < -25.5$) have a roughly constant intrinsic *I-K* colour. Our observations at the faint end of the CM relation are consistent with a linear correlation down to galaxies as faint as $M_K \approx -20$.

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